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by
T. R. Hofmann

NOX

Technical Report No. 36
June 26, 1961

PREPARED UNDER
OFFICE OF NAVAL RESEARCH CONTRACT
NONR 225(33), NR 088 003, AND
ADVANCED RESEARCH PROJECTS AGENCY, ARPA ORDER 196-61

RADIOSCIENCE LABORATORY
STANFORD ELECTRONICS LABORATORIES
STANFORD UNIVERSITY · STANFORD, CALIFORNIA

SOME CHARACTERISTICS OF F-LAYER IRREGULARITIES DEDUCED FROM BACKSCATTER SOUNDINGS MADE WITH A SLEWABLE ANTENNA HAVING A 2-DEGREE AZIMUTHAL BEAMWIDTH

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Radioscience Laboratory
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Stanford, California

SUMMARY

A study of the F-layer of the ionosphere made with an HF backscatter radar using a narrow-beam antenna has revealed a large number of irregularities in the size range from 50 km to 500 km in north-south extent. It has been possible to divide these irregularities into five types which have been named spot, line, split, step, and range variable. On the basis of 60 one-hour records, the probability of the occurrence of each type has been estimated (spot: 60 per cent; split: 90 per cent; others: less than 20 per cent of the time). North-south motion of the irregularities has been observed, but it occurs less than 10 per cent of the time and always with movement from north to south. When observed, the average velocity of movement is of the order of 1000 km/hr. On occasion, growth and fade of the irregularities has been noticed, with the time from start of growth to time of fade-out being of the order of 10 to 15 minutes.

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I. INTRODUCTION

Since November of 1960 a study of small-scale F-layer irregularities has been in progress at Site 514 of the Stanford Radioscience Laboratory. The work has had the following four specific aims:

1. It was desired to determine if small perturbations (areas of high or low ion density) in the F-region moved with time. If so, their velocities and directions, along with their size, were to be recorded.
2. Splits in range of the first hop return had been noticed previously, and it was desired to look more closely at this behavior.
3. For the small areas mentioned in (1) above that did not move, duration was to be studied.
4. Finally, all of the above were to be lumped together in consideration, and their correlation with magnetic activity determined.

A study of this nature was made possible through the use of an antenna array with a very narrow horizontal beamwidth. The antenna is an array of eight parallel rhombic antennas resulting in an aperture of 1600 feet. The beam (2° wide between half-power points at 15 Mc) is capable of being slewed automatically in one-degree steps, from 082° to 097° in azimuth.[1] This slewing is accomplished by means of relays, so that the antenna can be used simultaneously for transmitting and receiving.

Other studies similar in nature to this one have been conducted using the backscatter technique,[2] but these experiments have been

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[1]For further details on this antenna see: G. Barry, O. G. Villard, Jr., 'Characteristics of small-scale F-layer irregularities deduced from backscatter soundings made with a steerable narrow-beam antenna', Stanford Radioscience Laboratory, Technical Report No. 22, January 3, 1961, Contract Nonr 225(33), NR 087 090.

[2]See, for instance, J. F. Valverde, 'Motions of large-scale traveling disturbances determined from high-frequency backscatter and vertical incidence records', Stanford Radio Propagation Laboratory, Scientific Report No. 1, May 21, 1958, Contract AF19(604)-1830; and L. H. Tveten, 'Ionospheric motions observed with high frequency backscatter sounders', Journal of Research of the National Bureau of Standards - D. Radio Propagation, Vol. 65D, No. 2, March - April 1961.

primarily concerned with broad radar beams and large-scale moving disturbances. This report, it is believed, is unique in its use of a narrow slewable beam to study small-scale perturbations both moving and stationary.

In Tveten's report[3] several mathematical and physical models of ionospheric geometries are developed, some of which will be incorporated in this report.

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[3]L. H. Tveten, *Op. Cit.*

II. PROCEDURE

The equipment used consisted of the aforementioned antenna, a Granger Associates 100-kw peak power pulse transmitter, and a Hammarlund SP-600 receiver used in conjuntion with a logarithmic detector. The data recording method was magnetic tape via an Ampex FR 100 tape recorder.

With the antenna beam being automatically slewed through 16°, the transmitter was pulsed at 10 pps with a pulse width of 0.4 ms. The receiver (used in a duplexer arrangement with the transmitter to permit using the array for both transmitting and receiving) was set with a 3-kc bandwidth. The frequency of 15.3 Mc was chosen in order to eliminate any variables due to frequency. The receiver IF was run through a logarithmic detector whose output was recorded on tape. The tape was later displayed on an intensity modulated oscilloscope and filmed on 35mm film. Each tape was filmed with three different gain settings with corresponding range settings (e.g., one gain setting corresponded to looking just at the upper portion of the first hop and was filmed with a range setting of 2000 - 5000 km depending on how far out the first hop was).

The time of day at which these tests were run varied from 0800 to 1600 local time with the majority of tests taking place before 1200. Usually the tests were 120 minutes long, although several were only 40 or 80 minutes in length. As yet no tests have been run after dusk. The goal was 40 to 120 minutes of tape per day, but other experiments involving the use of the same equipment caused this goal to be unattainable. As a result, the influx of data has been steady at times, but sporadic in the long run.

III. RESUME OF TERMS

At this time it is convenient to describe the types of irregularities noticed. The irregularities have been divided into five specific types as follows:

1. *Spot* - This is an irregularity in the range-azimuth backscatter display which is well-defined in both range and azimuth. It usually consists of an intensified region in the echo pattern which corresponds to an area in the ionosphere from 2° to 5° in width and from 100 km to 500 km in depth. An example of the spot irregularity can be seen in Fig. 1.

2. *Line* - This is the same as the spot except that it is very thin in slant range (about 50 km) so that it appears as a line instead of being diffuse like the spot. See Fig. 2.

3. *Step* - This type of irregularity appears as a fairly sharp discontinuity in range of a return which is otherwise constant in range. See Fig. 3.

4. *Split* - Noticeable division in range of backscatter returns for a given hop within the range limits of that particular hop. For instance, Fig. 4 shows returns at several discrete ranges which all together make up the first hop.

5. *Range Variable* - Backscatter return variable in range as a function of azimuth. (Differs from the step in that it is continuously variable over several degrees instead of being discontinuous from one sector to the next.) See Fig. 5.

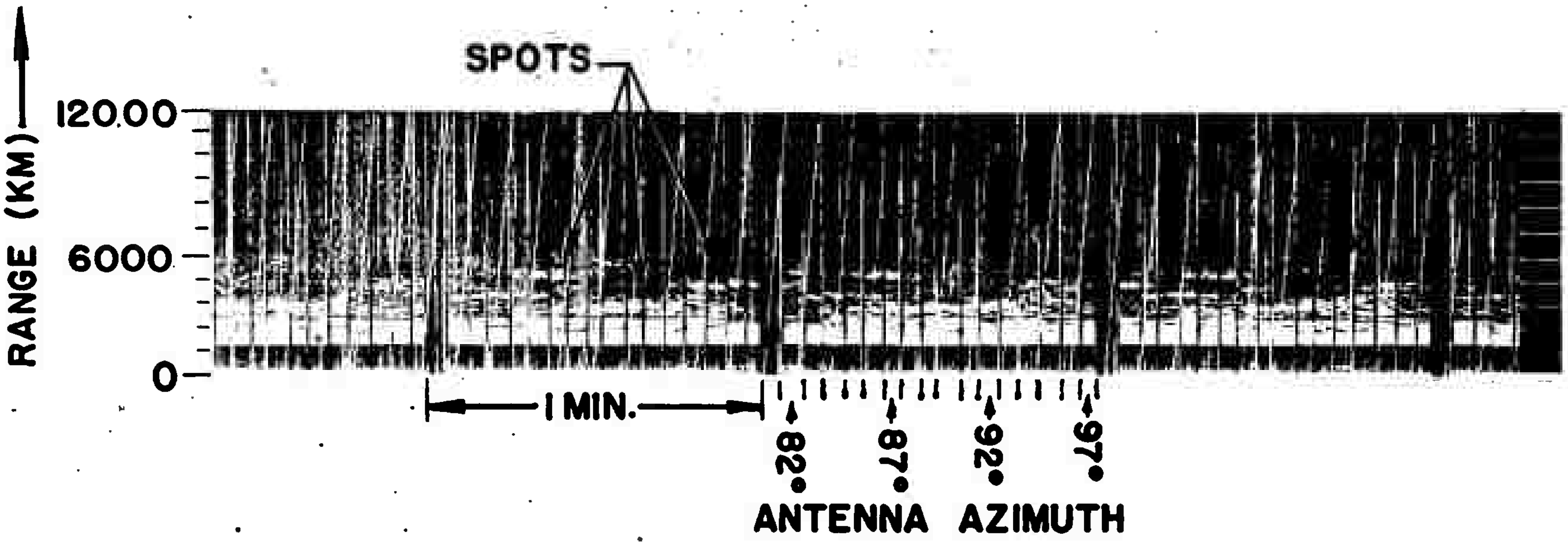

FIG. 1. EXAMPLE OF SPOT IRREGULARITY.
DATE: 20 MARCH 1961
TIME: ABOUT 2300 GMT

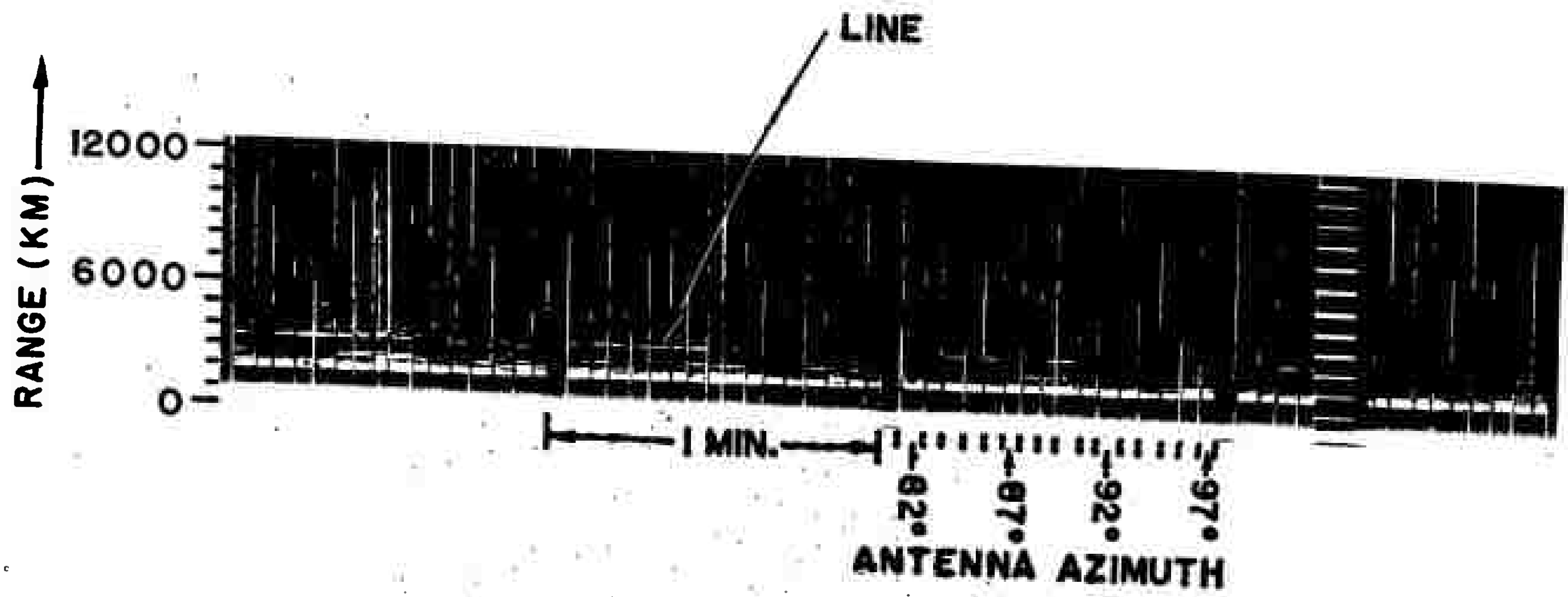

FIG. 2. EXAMPLE OF LINE IRREGULARITY (SECOND HOP).
DATE: 10 MARCH 1961
TIME: ABOUT 2300 GMT

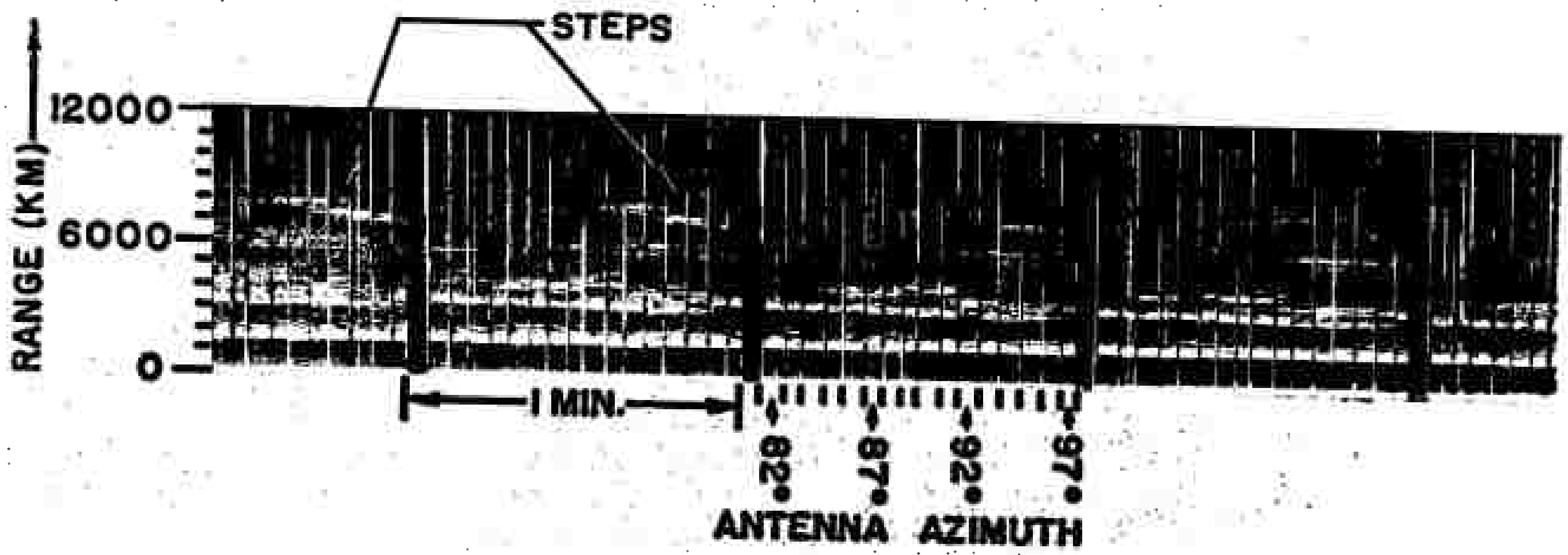

FIG. 3. EXAMPLE OF STEP IRREGULARITY (STEP IN FOURTH HOP).
DATE: 13 MARCH 1961
TIME: ABOUT 2300 GMT

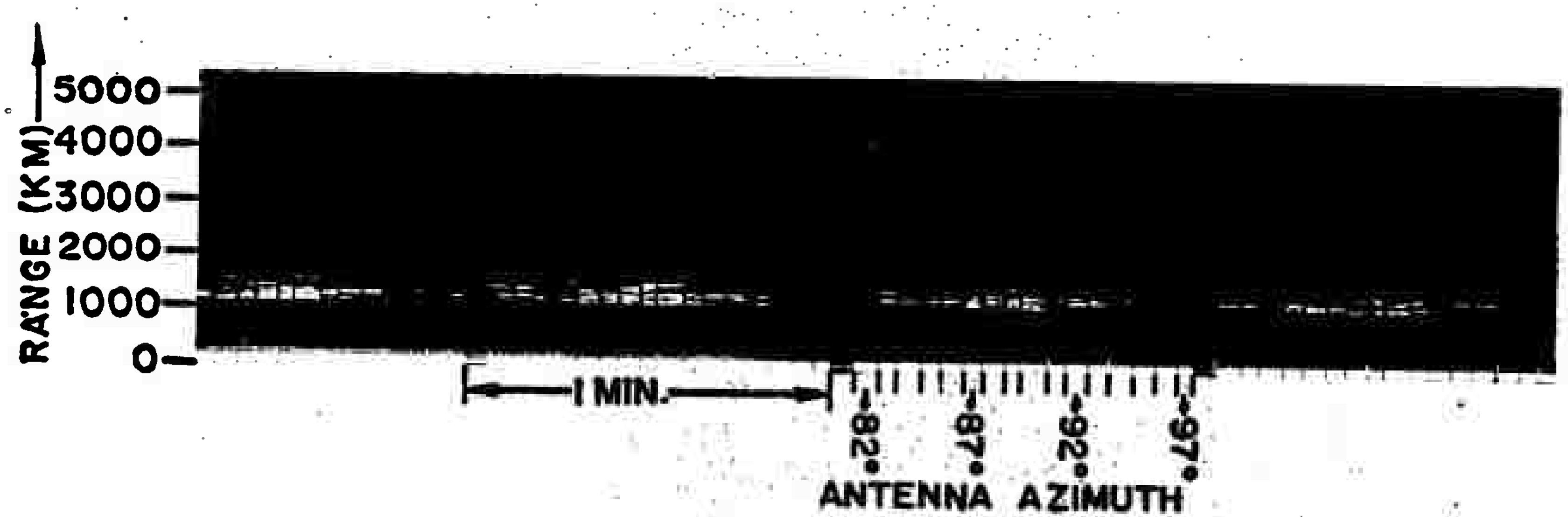

FIG. 4. EXAMPLE OF SPLIT RANGE IRREGULARITY (SPLITS IN FIRST HOP).
DATE: 18 FEBRUARY 1961
TIME: ABOUT 2100 GMT

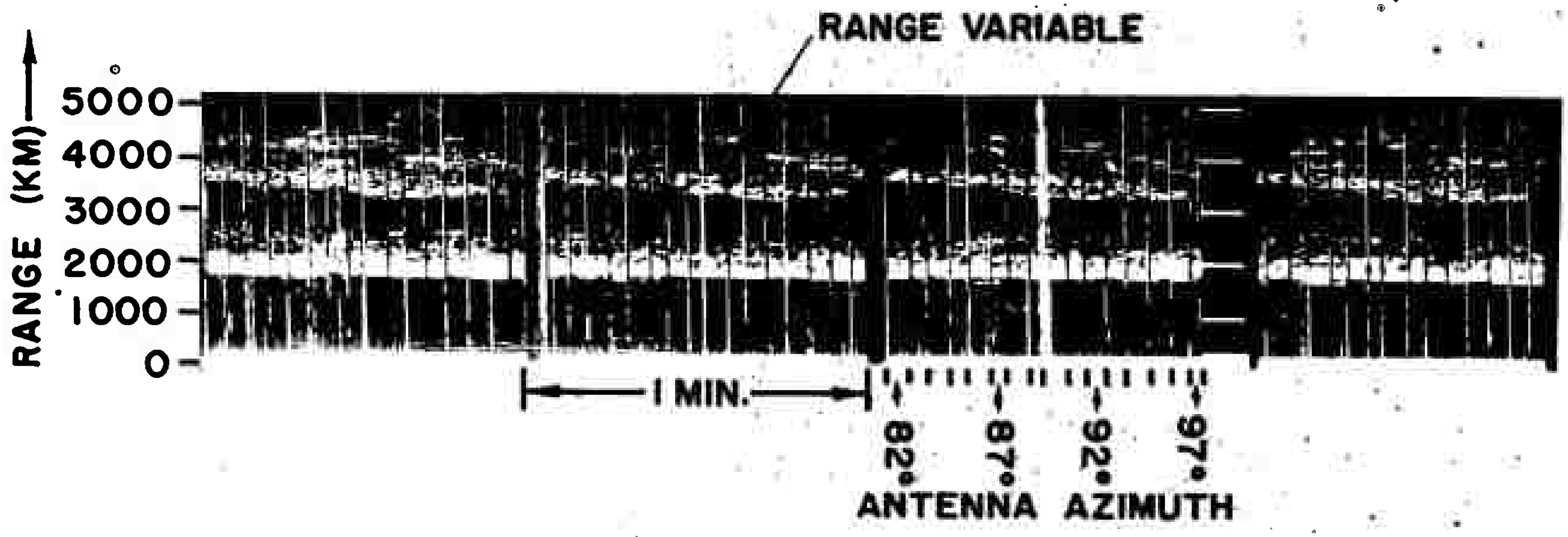

FIG. 5. EXAMPLE OF RANGE VARIABLE IRREGULARITY IN SECOND HOP.
DATE: 13 MARCH 1961
TIME: ABOUT 2330 GMT

IV. TEXT

Early recording was via a facsimile record which, of necessity, gave output in only one form. More flexibility in data processing was needed, so a change was made to magnetic-tape data recording. To obtain a large dynamic range, a logarithmic detector with a 60-db range was used.

Each record has been examined for behavior tying in with the five specific aims mentioned in the Introduction. In the case of moving disturbances, it is sometimes hard to determine whether there is really movement of the spot or just a rapid fade. Those disturbances that do seem to have definite movement, however, have been tabulated. In the case of fluctuating disturbances, it is very much easier to arrive at a tabulation, as the growth and fade is very noticeable on the records. When more than one F-layer hop is present, the patterns become highly variable, and due to the complexity of the ray path geometry for more than one hop, no attempt will be made to explain this behavior on the basis of a physical model.

Probably the easiest phase of this study was the determination of the degree of correlation between magnetic activity and backscatter activity. The results of the study, however, must be considered in the light of the source of information. A_k magnetic indices (24-hour averages) were obtained from Fort Belvoir in Maryland, and the question as to how accurately they represent magnetic behavior at the point of F-layer reflection must be kept in mind when reviewing the results obtained.

In order to use these indices, each backscatter record was arbitrarily graded as to its activity. Grades ranged from zero (indicating no activity---uniform returns) to five (indicating highly non-uniform behavior---many perturbations). The A_k index corresponding to a particular day was compared with the records for that day, and a plot was made of record activity versus magnetic index. Figure 6 shows a plot of the activity of all the records taken on tape versus the A_k indices. (Facsimile records are not included since during this portion of the experiment the radio frequency was allowed to vary, introducing a further complexity.)

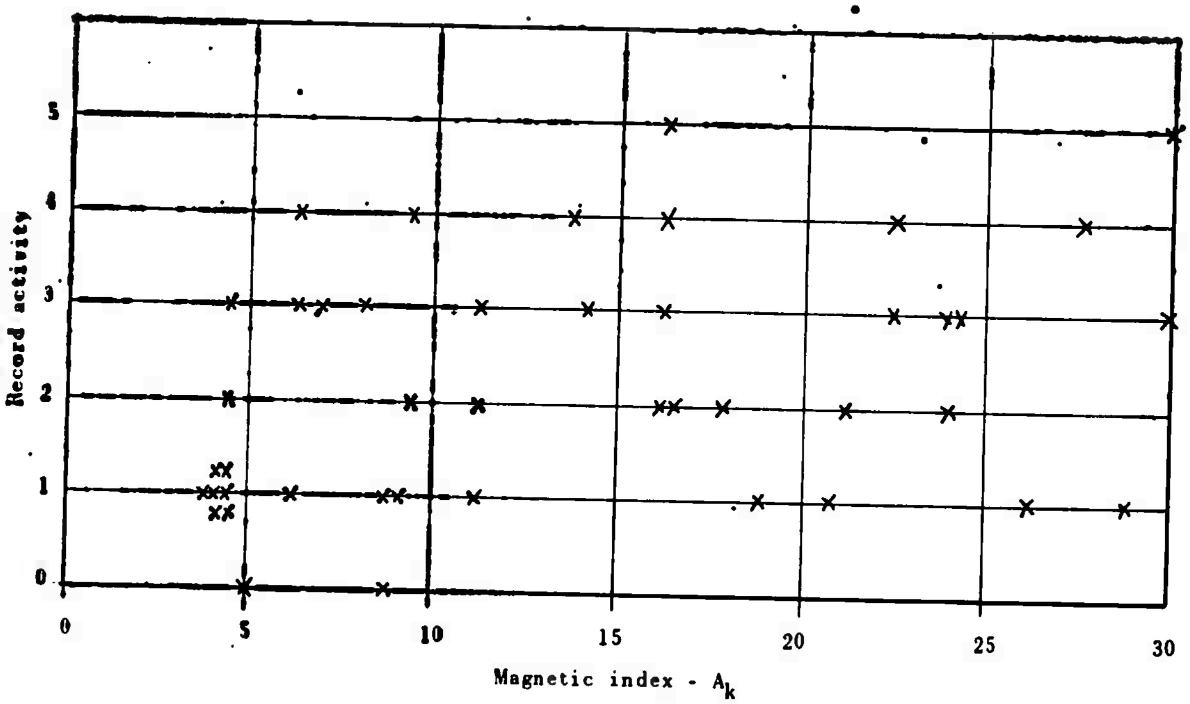

FIG. 6. A_k INDICES FROM FORT BELVOIR VS RECORD ACTIVITY BASED ON ARBITRARY SCALE.

Split range behavior has been noticed since the beginning, and a good portion of this report will now be spent in presenting a possible physical model to explain this behavior. 'Split range perturbation' is the name given to the splitting of backscatter returns into many discrete range intervals, so that each hop (depending on its size) is made up of several of these returns (Fig. 4).

That the splits were actually due to ionospheric characteristics (rather than equipment) was determined by varying the characteristics of the equipment used (both for receiving and for recording the backscatter), with the finding that the relative spacing of the splits was unchanged. Probably the most convincing of the tests conducted, consisted of both halving and doubling the time scale of the equipment,[4] resulting in no noticeable change in the spacing of the splits. Had the equipment been the cause of this behavior, the spacing should have changed very noticeably.

In his report Tveten[5] presents the basis of the model used here. It consists of a simple curvature in the ionospheric reflecting layer which causes focusing of the transmitted rays, but what is more important is that it results in the combination of many ray paths into constant time delay paths which would then show up on the amplitude display as a peak at that delay time. This curved section of the ionosphere would correspond to a segment of an ellipse whose foci are the transmitter and the ground reflection point (Fig. 7). However, as Tveten mentions, it is not necessary that the reflecting section be exactly elliptical; any concave downward curvature would provide some constant, or nearly constant, delay path bunching.

This report is concerned with spacings on the records of about 100 km; in the ionosphere this would correspond to distances of the order of 50 km between peaks of ripples. The postulation then is that curves of constant ion density in the ionosphere are rippled in a wave-like manner, and that these waves vary in accordance with winds or tides in the ionosphere.[6]

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[4]Doubling and halving the time scale consisted of the following (taken with each of two different detectors):

Ten minutes of data were recorded with the time scale set by a transmitted pulse width of 400 μsec and a receiver bandwidth of 8000 cps.

Next, ten more minutes of data were recorded with a doubled time scale; i.e., a pulse width of 1000 μsec and a receiver bandwidth of 3000 cps. (This is slightly more than doubled, but the receiver had fixed BW positions of 3, 8, and 13 kc.)

The last ten minutes of data were recorded with a halved time scale (pulse width: 250 μsec; bandwidth: 13,000 cps).

These six sets were compared with each other, and there was no noticeable change in the spacing of the splits. It was concluded that the effect was ionosphere induced.

[5]L. H. Tveten, *Op. Cit.*

[6]Also postulated by Pierce, See: J. A. Pierce, 'The reception of radio echoes from distant ionospheric irregularities', Physical Revue, Volume 57, No. 2, pp. 95-105, January, 1940.

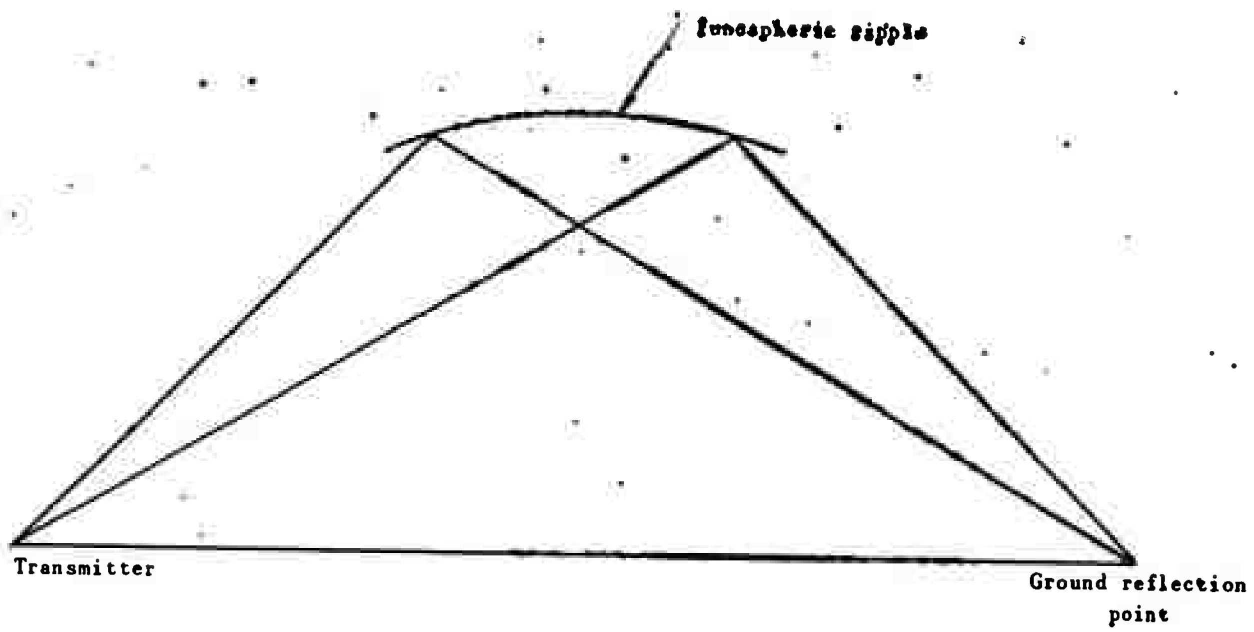

FIG. 7. FOCUSING MODEL.

Due to the restrictions placed on the data, no attempt will be made to say anything about the winds or tides except where they cause noticeable movements in larger-scale perturbations (the spots).

Using the models in Figs. 8 and 9 an attempt will now be made to find the approximate depth (between the deepest and shallowest points of the ripple) that would be necessary to provide the constant delay paths observed. For purposes of calculation, the virtual height of the reflection point will be assumed to be 300 km, and the ground range to the point of reflection is taken as 700 km, which is average for one-hop returns in this experiment. Since y originally is taken as the height to the deepest part of the ripple, Δz_2 is taken as 12.5 km to correspond approximately to movement from the deep point to the midpoint of the assumed variation of ion density (Fig. 9). The following calculations then determine the change in y from the given changes in z_2.

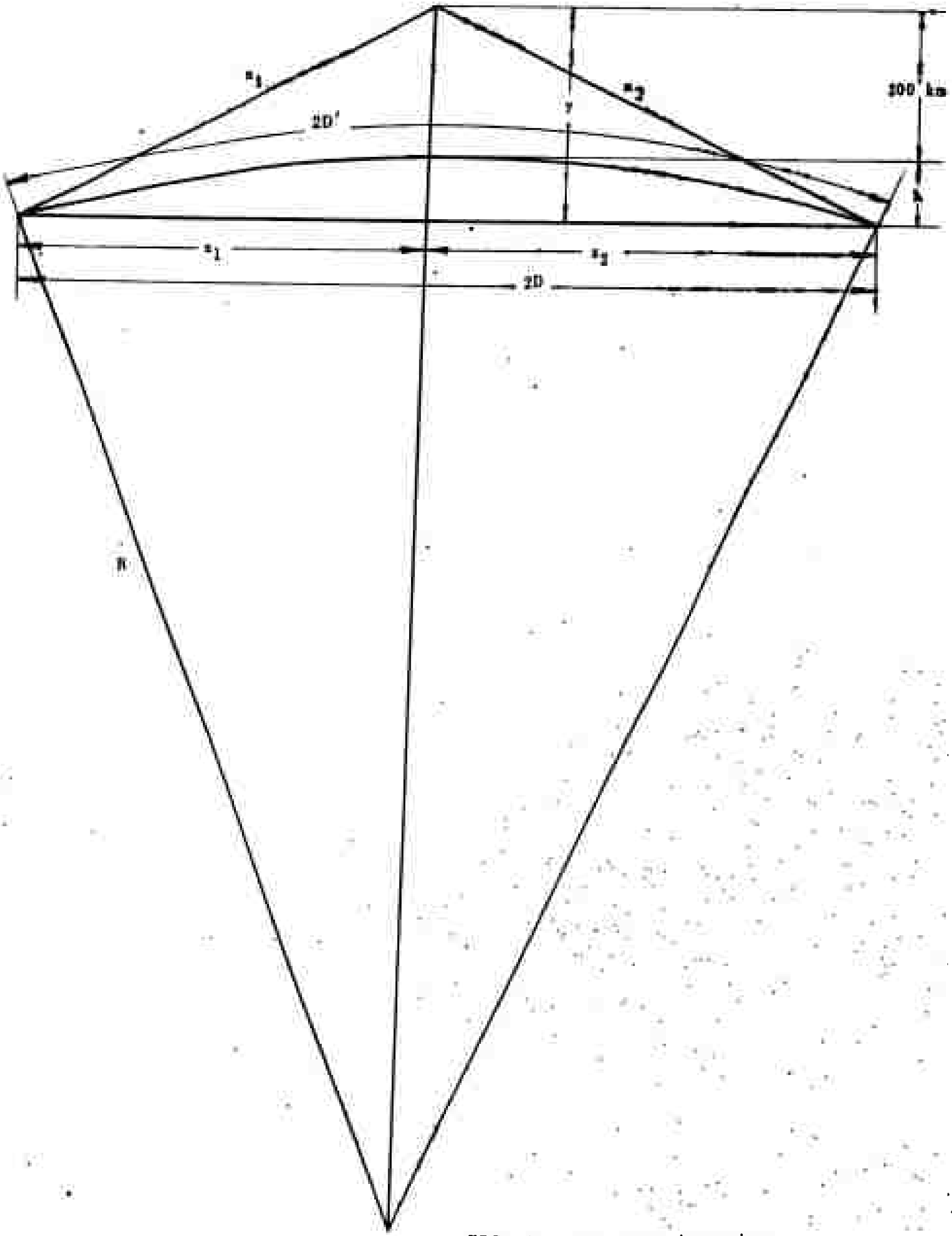

FIG. 8. RAY PATH GEOMETRY.

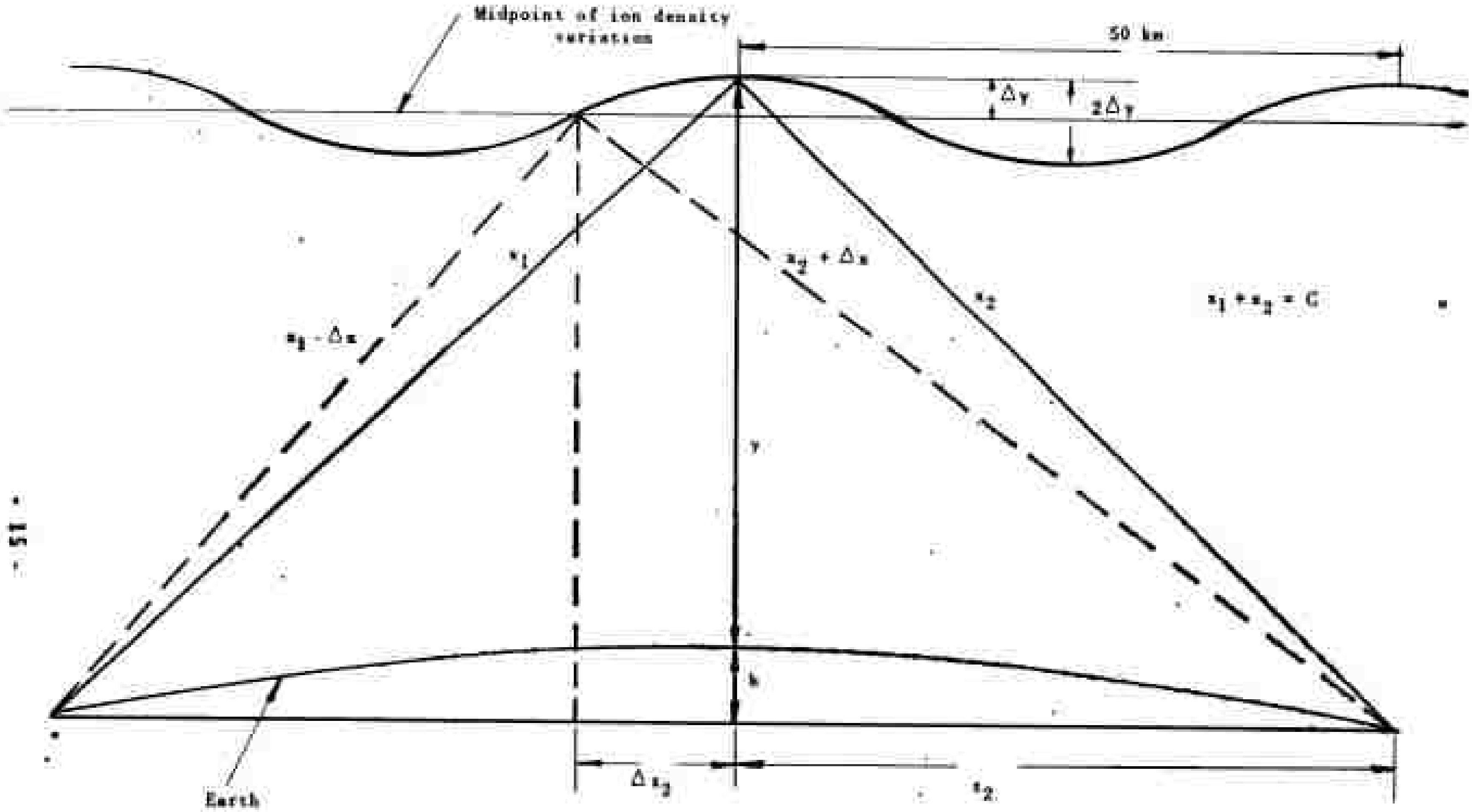

FIG. 9. CHANGES IN RAY PATH GEOMETRY FOR CHANGES IN IONOSPHERIC REFLECTION POINT.

The basic equations are

$$x_1 + x_2 = C \qquad C = (y^2 + z_1^2)^{1/2} + (y^2 + z_2^2)^{1/2}$$

$$x_1^2 = y^2 + z_1^2$$

$$x_2^2 = y^2 + z_2^2$$

$$z_1 = 2D - z_2$$

C is a constant and is equal to the length of the constant delay path.

Solving these for y in terms of z_2 gives:

$$y^2 = (C^2 - 4D^2)^2/4C^2 + 2(1 - 4D^2/C^2)Dz_2 + (4D^2/C^2 - 1)z_2^2$$

Taking the derivative of y with respect to z_2 leaves

$$2y \frac{dy}{dz_2} = 2(1 - 4D^2/C^2)D + 2(4D^2/C^2 - 1)z_2$$

or for small Δy

$$2y \Delta y = (2D - 2z_2 - 8D^3/C^2 + 8D^2 z_2/C^2) \Delta z_2$$

Since $z_2 = D + \Delta z_2$,

$$2y \Delta y = (-2 \Delta z_2 + 8D^2 \Delta z_2/C^2) \Delta z_2$$

or

$$\Delta y = [(\Delta z_2)^2/y](4D^2/C^2 - 1)$$

This is the desired result, since Δy can now be calculated:

$$\Delta z_2 = 12.5 \text{ km} \qquad h = R - (R^2 - D^2)^{1/2}$$

$$y = 300 \text{ km} + h \qquad D' = 700 \text{ km}$$

$$D = R \sin(D'/R) \qquad R = 6367 \text{ km}$$

Since $D'/R << 1$, $\sin(D'/R) \approx D'/R$ giving

$$D \approx R(D'/R) = D' = 700 \text{ km}$$

then

$$h = R - (R^2 - D^2)^{1/2} \approx 40 \text{ km}$$

$$y = 340 \text{ km}.$$

Since C is constant it can be calculated for the case wherein $x_1 = x_2$ and $z_1 = z_2 = D$. Thus

$$C = 2x = 2(y^2 + D^2)^{1/2} \approx 1560 \text{ km}.$$

Finally

$$|\Delta y| = [(12.5)^2/340][(1400/1560)^2 - 1] \approx 90 \quad \text{m}.$$

Using $\Delta y = 100$ m, we see that the total variation in height from the lowest to the highest points of the ripple need only be 200 meters. Variations as small as this are very reasonable to expect since much larger variations have been tabulated via ionograms.

So far the considerations have been entirely with straight ray paths; if actual ray paths (which are curved due to the constantly changing dielectric constant) are considered, the situation becomes complex.[7] Figure 10 shows a sketch of the rippled F-layer where the rippled lines are lines of constant ion density. The figure shows two ray paths (typical of those calculated on the basis of a Chapman layer)[8] superimposed upon the rippled ionosphere. (Remember that this figure is only a crude sketch and does not represent any particular ion density gradient.)

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[7] It is conceivable that a digital computer program could be written to handle the analysis on a more or less rigorous basis.

[8] A. M. Peterson, O. G. Villard, Jr., (Title SECRET), Stanford Radioscience Laboratory, Technical Report No. 20, November 20, 1960, Contract Nonr 225(33), NR 087 090. SECRET

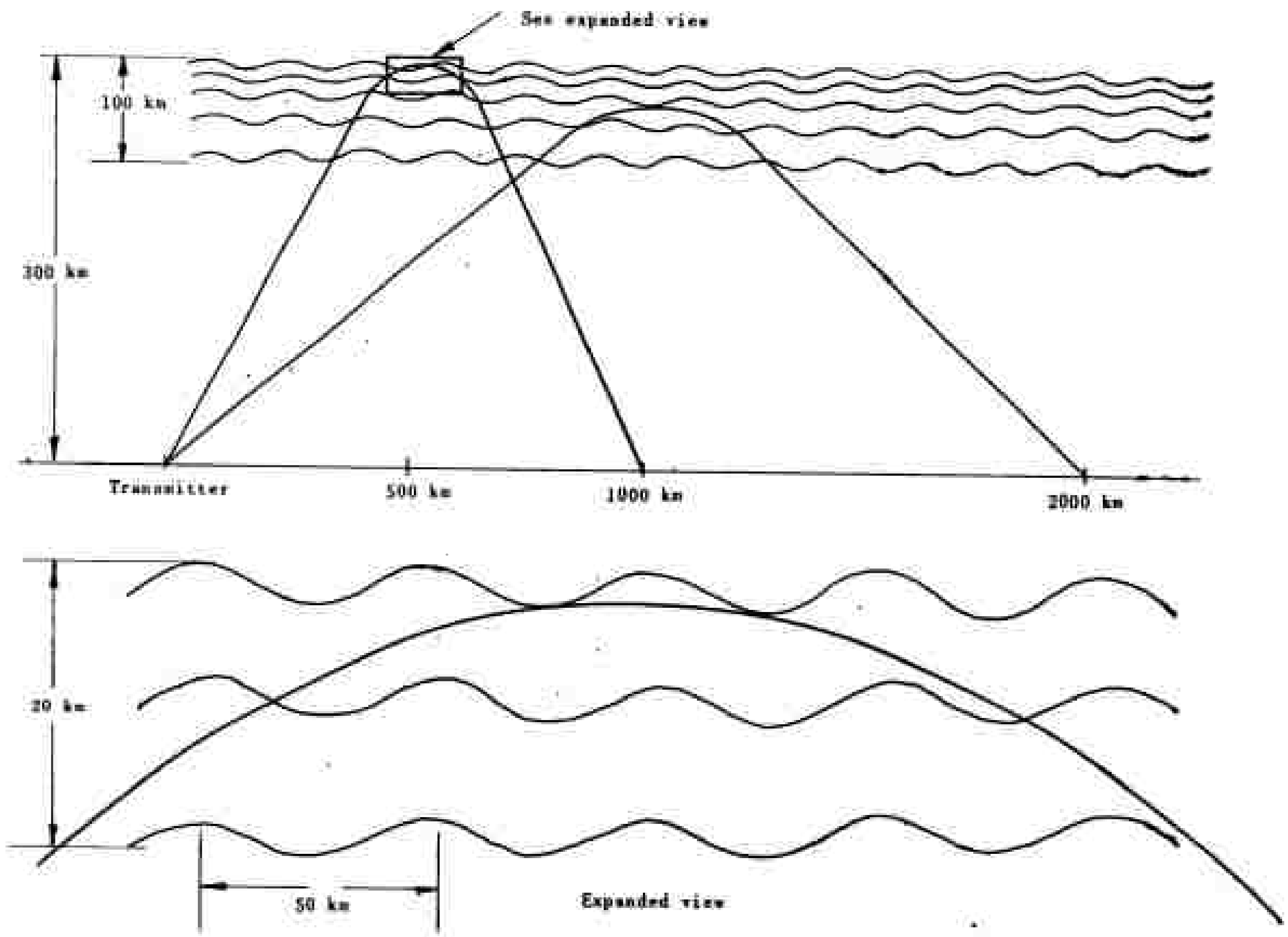

FIG. 10. RIPPLED IONOSPHERE AND TYPICAL RAY PATHS.

It can be seen from these ray paths that as the ray reaches its curved peak, it spends considerably more time within a section of assumed constant ion density than it does in the corresponding sections on the way up or down. The postulation then is that the effect on a particular ray due to the ripples is small on the way up, but is greatly enhanced at the peak---enough so that the necessary focusing effect is induced.

That the effect on the ray path due to the ripples below the peak is small, appears reasonable if it is remembered that the ripples are extremely small (of the order of a sinusoid 200 meters peak to peak with a period of 50 kilometers). Thus lines of constant ion density appear nearly unrippled until the ray is bent to a path nearly parallel to the ripples.[9] When this happens, even the very slight variations postulated have the large effect calculated previously.

This completes the postulation of a physically acceptable ionosphere which would produce the splitting effect noticed on the records. It must be kept in mind, however, that the latter part of this discussion has been far from rigorous, but it was felt necessary in order to make the model as complete as possible. It is only a suggestion, but it is felt to be a justifiable one.

On the basis of this ionospheric model, the line irregularity can be explained as ray path focusing by a single ripple where the surrounding ripples have been disturbed so that their focusing effect has been eliminated. This would have the effect on the record of giving a single narrow return separated from other returns by more than a hundred kilometers, but this, by definition, is a line irregularity.

---

[9] The 200-meter figure was obtained with D = 700 km. As the ray becomes nearly parallel with the center line of the ripples, the effect is the same as a large increase in D, and thus C, which (from the equations) is seen to decrease Δy even more.

V. RESULTS

In forty-six of the sixty records reviewed,[10] there are spot irregularities (in the first[11] or second hop) which are either constant with time, or move, or fade. In the fourteen records which did not have this irregularity, twelve had no irregularities (except splits) at all. The spot sizes vary from 15 km to 300 km in width. Of the spots noticed, about 80 percent of them faded in and out with time. The duration does not seem to be a linear function of size although the very large spots (of the order of 8° in width) do last longer than the smaller ones. With the smaller ones the duration lies between 4 minutes and 15 minutes, although in rare instances a spot one degree wide will appear and disappear in the space of one minute. The line spot acts like an ordinary spot except that it is much rarer, appearing in only about fifteen records. The rarity of the line irregularity is understandable in view of the explanation of this irregularity given in the text.

To be classified as a moving irregularity, a perturbation had to satisfy the criterion that it move at least its total width in azimuth. On this basis only nine of the sixty records contained moving irregularities,[12] and four of these nine contained eight of the fourteen moving irregularities noticed. The velocities varied from 500 km/hr to 1500 km/hr with the average close to 1000 km/hr. Size had no apparent effect on velocity (see Table I). All of the movements noticed were movements from north to south---none in the opposite direction.

---

[10] Average length of the records is two hours each.

[11] There have probably been more spots in the first hop than our method of recording has indicated.

[12] It is necessary to re-emphasize at this point that this report has been written to deal only with small-scale irregularities. Thus, detection of movement was usually possible only in the cases of movement in azimuth. No attempt has been made to define movement with respect to range since such movement would have had to be contained in one hop, and this behavior was never noticed.

TABLE I. TABULATION OF MOVING IRREGULARITIES

N-S width of irregularity (km)	Range to ionosphere (km)	Extent of N-S movement (km)	Approximate N-S velocity (km/hr)
160	1200	320	1100
210	4200	500	1500
130	7600	130	1000
100	5800	100	700
80	1100	80	500
150	4400	150	1100
250	3800	430	1200
100	2200	250	600
100	2200	170	700
100	2200	100	700
100	2200	550	1500
150	3000	500	1000
150	3000	200	1200
270	5400	1000	2000

The step discontinuity appears to be quite rare, as it was noticed in only four records, but twice in each of two of the records. It has never lasted longer than 10 minutes, and it has always been closely followed by the range-variable irregularity. In four of the six times it has been noticed, the step has moved in range just prior to the change to the range-variable behavior. The range-variable irregularity is not so rare, appearing in twelve records in varying degree but always with the southern end being the end closer in range. The length of time this behavior appears to last is between 10 minutes and 30 minutes.

Of the five irregularities classified in this report, the split was the most commonly noticed. It appears in fifty-three of the sixty records; and in every record where it appears (except one), it is a continuous behavior lasting the entire length of the record. In the one exception the record changed from a record of apparent turbulence to one of the normal split range behavior. In the seven records which contained no split range irregularities, the individual hops appeared very turbulent in make-up (Fig. 11). The splits appear in all hops, which would have been expected on the basis of the model.

From Fig. 6 it can be seen that there is no apparent correlation between the record activity and the A_k index from Fort Belvoir. This suggests that long-term (24 hour average) magnetic disturbances have no apparent effect on the irregularity behavior of the ionosphere, but it does not eliminate the possibility that relatively rapid changes in magnetic activity do have an effect.

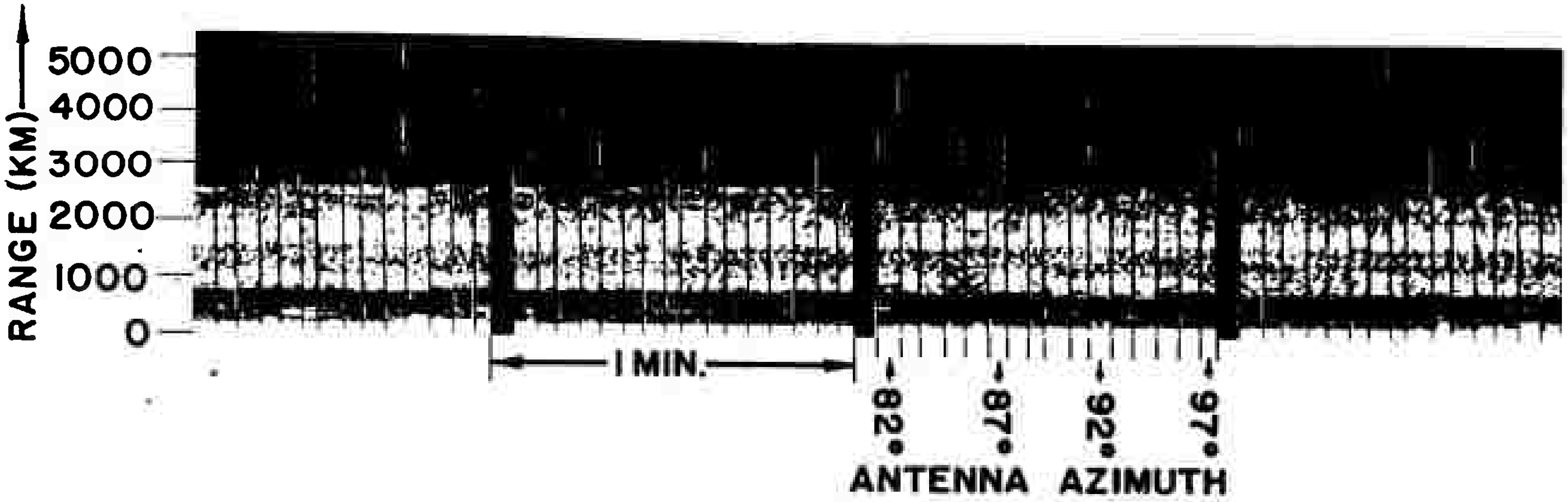

FIG. 11. EXAMPLE OF RECORD WITH NO SPLIT RANGE IRREGULARITY.
DATE: 17 MARCH 1961
TIME: ABOUT 1900 GMT

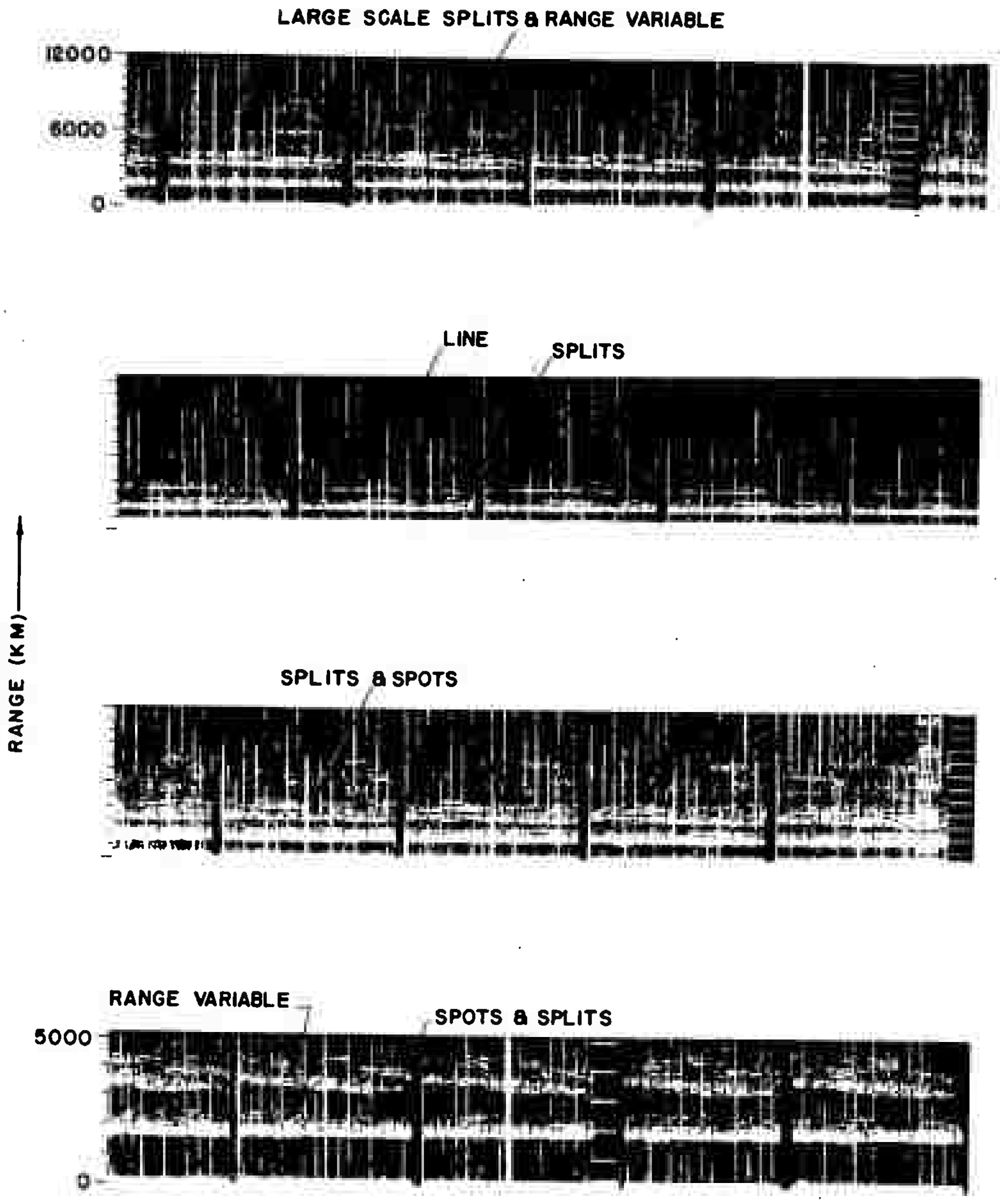

FIG. 12. EXAMPLES OF TYPICAL RECORDS.
DATES: SECOND PICTURE - 10 MAY 1961
OTHERS - 13 MAY 1961
TIMES: ALL ABOUT 2300 GMT

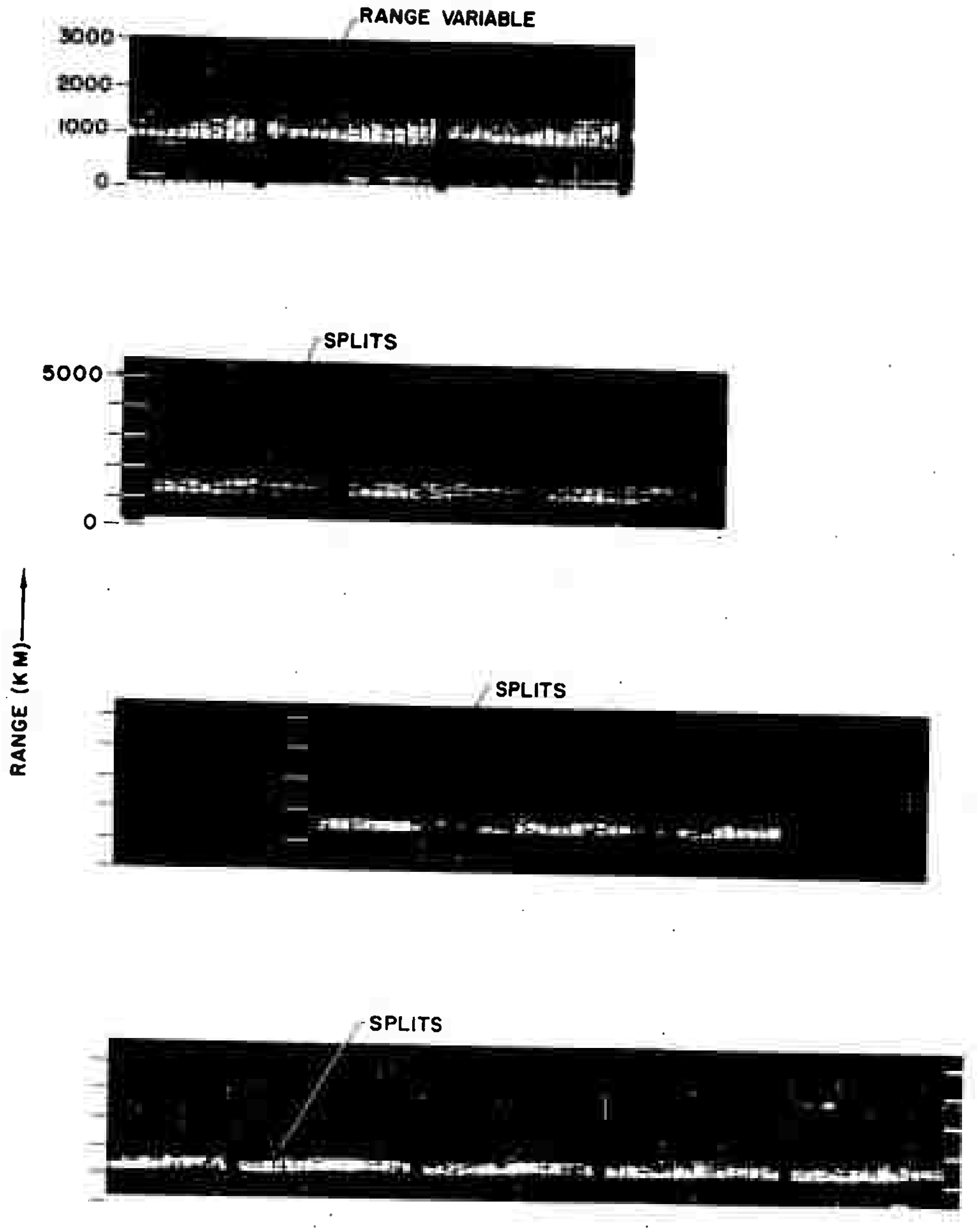

FIG. 13. MORE EXAMPLES OF TYPICAL RECORDS.
DATES: VARIOUS
TIMES: BETWEEN 1700 AND 1900 GMT

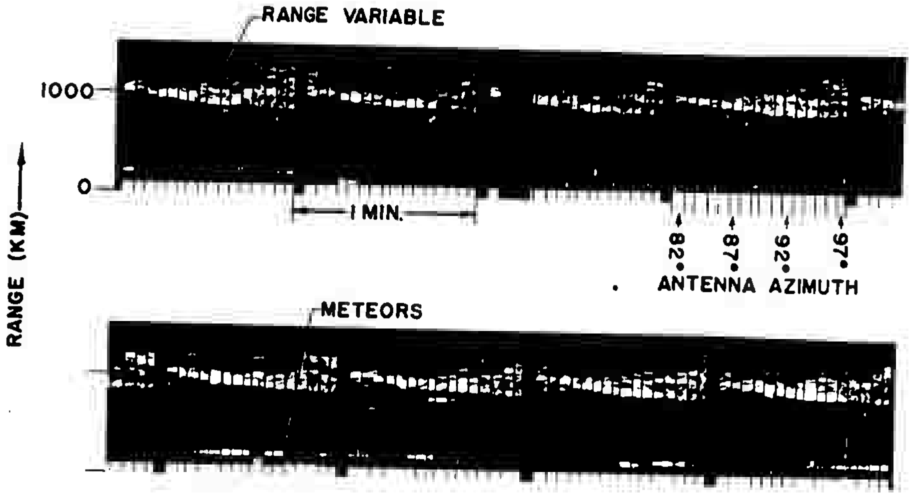

FIG. 14. EXAMPLE WITH EXPANDED SCALE.
DATE: 10 MAY 1961
TIME: ABOUT 1600 GMT

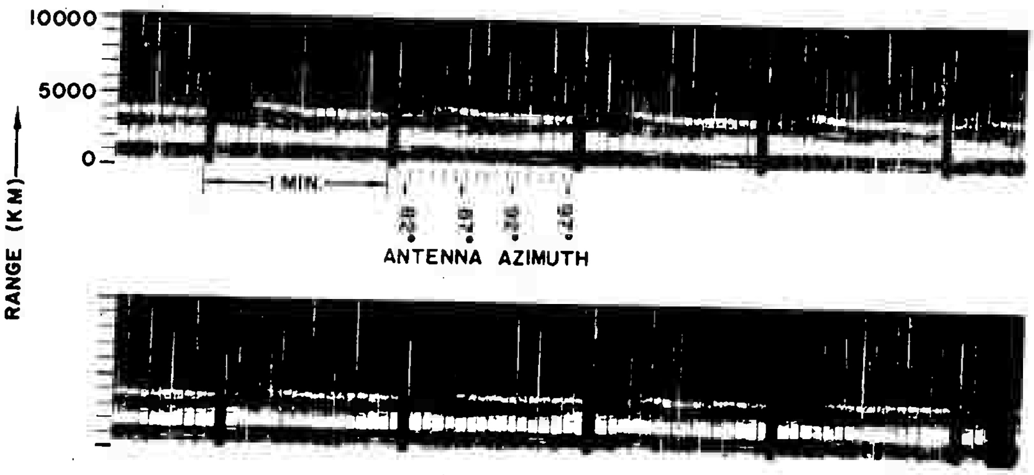

FIG. 15. SECTION OF RECORD JUST PRECEDING THAT IN FIG. 14 (NOT EXPANDED SCALE).
DATE: 10 MAY 1961
TIME: ABOUT 1600 GMT

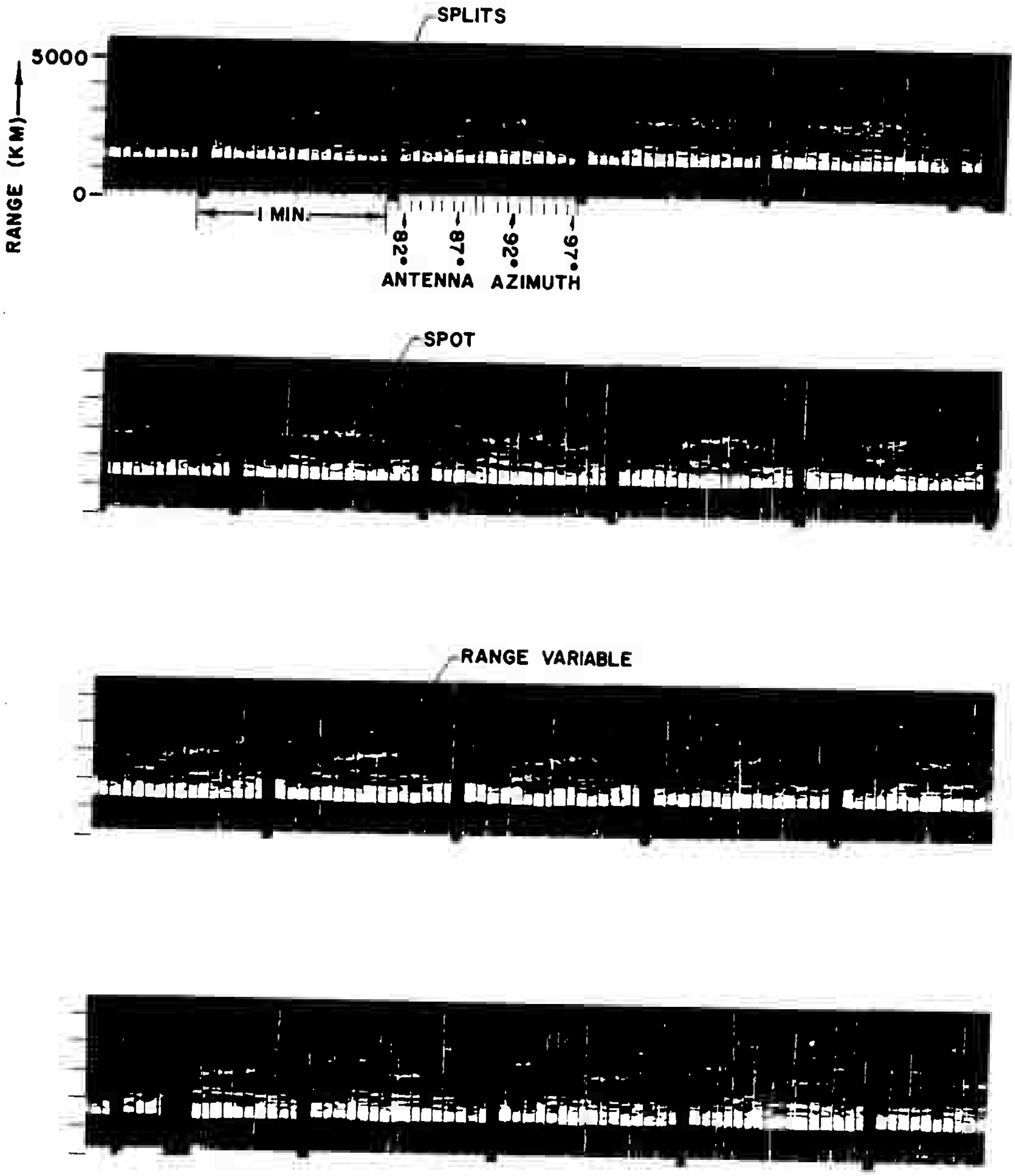

FIG. 16(a). EXAMPLE SHOWING CONTINUOUS RECORD OF ABOUT 40 MINUTES LENGTH [INCLUDING PART (b)].
DATE: 20 MAY 1961
TIME OF START: ABOUT 2230 GMT

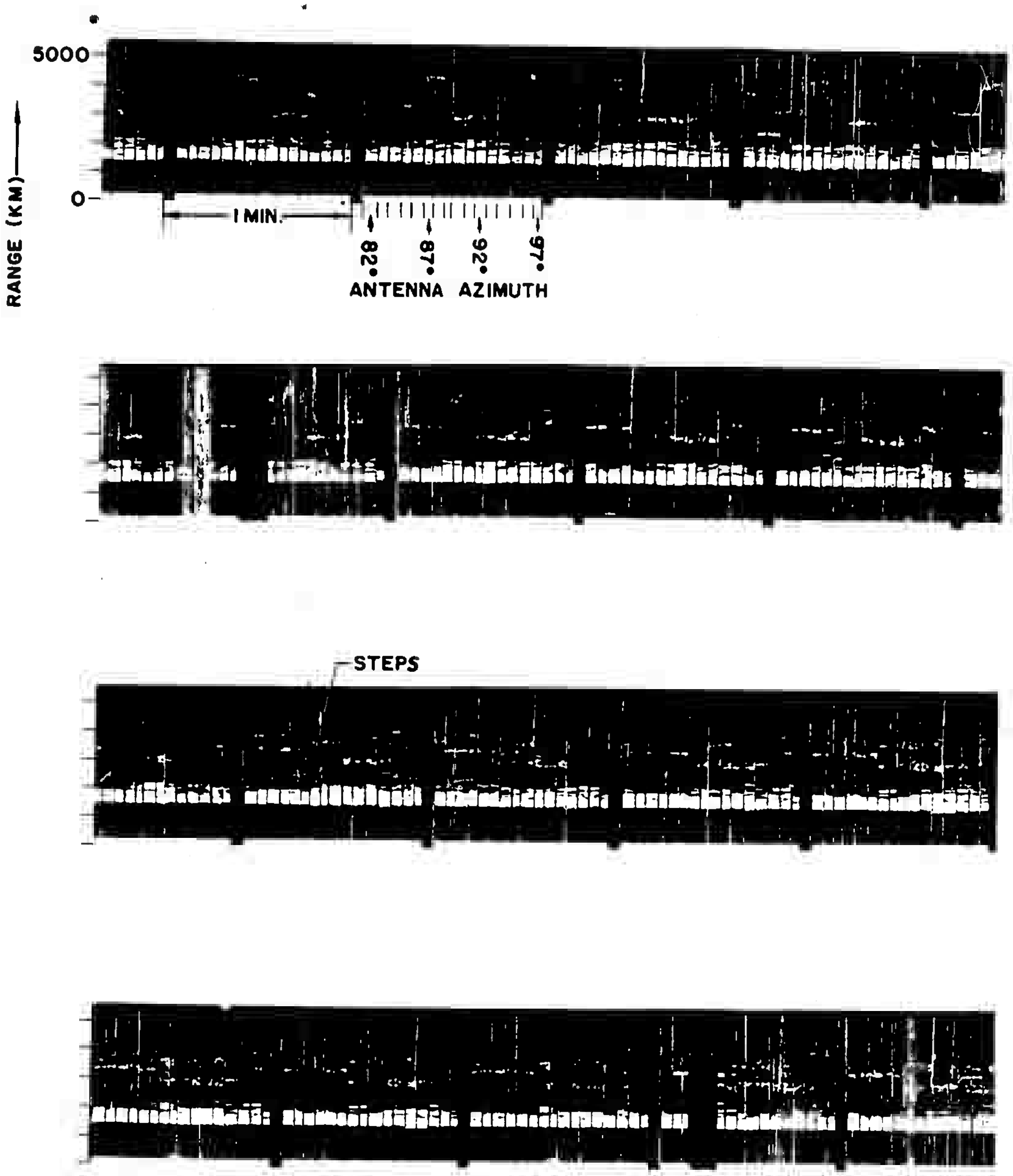

FIG. 16(b) CONTINUATION OF FIG. 16(a).

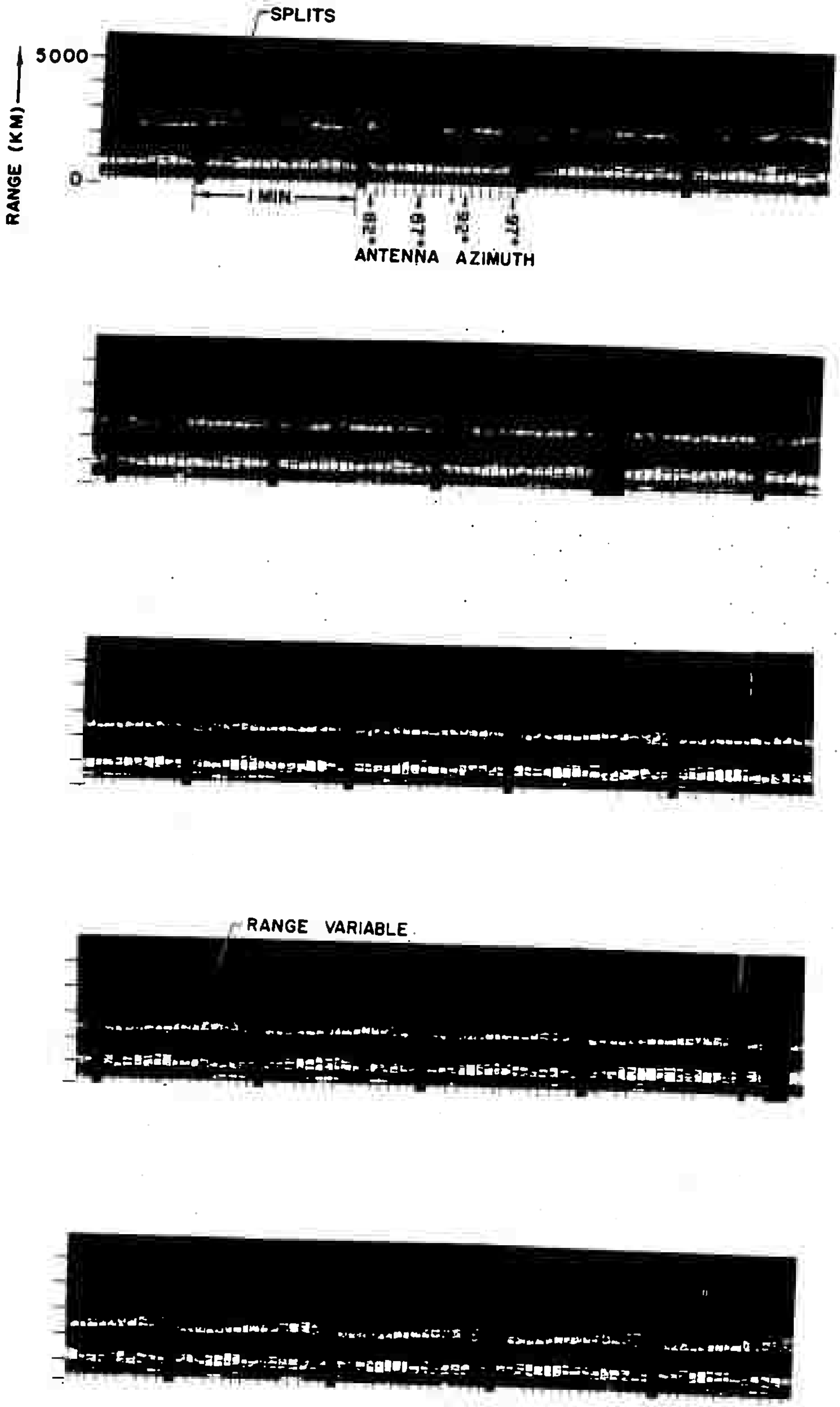

FIG. 17. ANOTHER EXAMPLE OF CONTINUOUS RECORDING (ABOUT 23 MINUTES LONG).
DATE: 8 MAY 1961
TIME OF START: ABOUT 1830 GMT

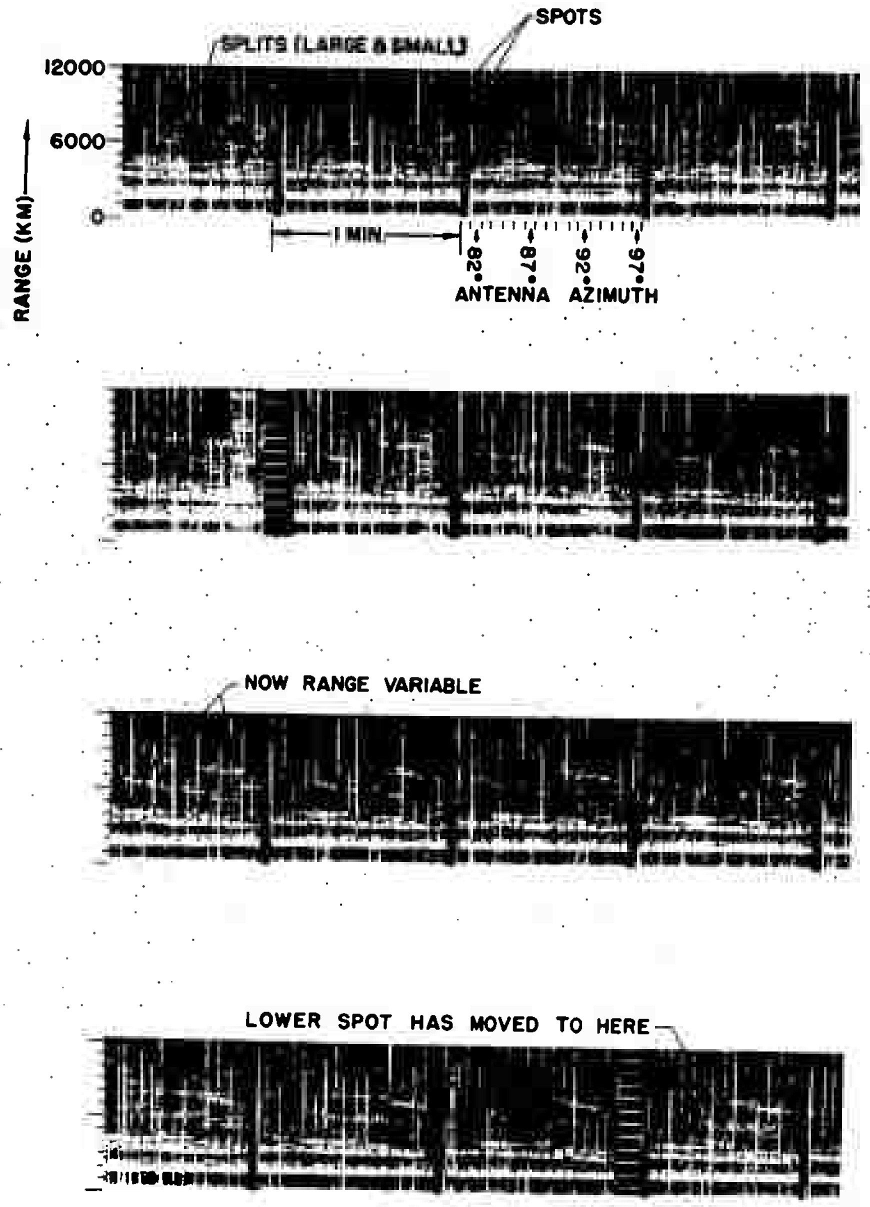

FIG. 18. RECORD SHOWING DEVELOPMENT AND MOVEMENT OF RANGE VARIABLE IRREGULARITY.
DATE: 13 MAY 1961
TIME OF START: ABOUT 2330 GMT

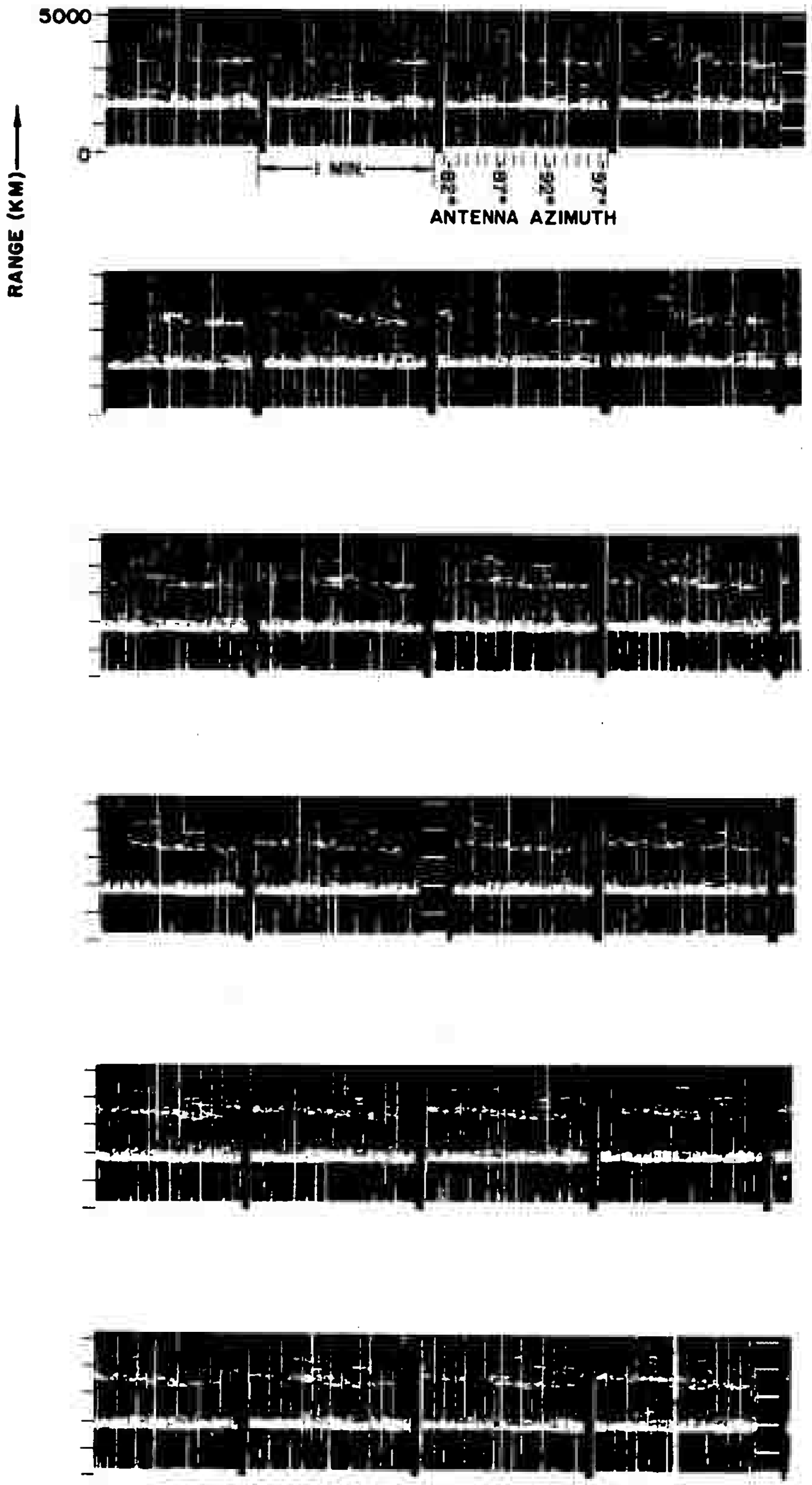

FIG. 19. ANOTHER CONTINUOUS RECORD EXAMPLE.
DATE: 13 MAY 1961
TIME OF START: ABOUT 2300 GMT

VI. CONCLUSIONS

The records seem to indicate that each small-scale irregularity of the F-layer can be classified as one of four different types. The types, as listed earlier, are the spot, step, split, and range variable (the line irregularity has been included within the scope of the spot).

The split is most common, and the chances of seeing this behavior to the east at any time interval during daylight (at point of reflection) are probably better than 90 per cent.[13] The spot is less common, but during any hour interval of daylight chances of seeing it are probably better than 60 per cent. The range variable irregularity is relatively rare, appearing probably less than 20 per cent of the time. At present the step discontinuity is a rare occurrence, and no attempt can be made to say how often this might occur.

All of the irregularities (except the split) seem equally likely to move, but very few of them (fewer than 10 per cent) do. When they do move, however, they appear to move in a southerly direction[14] with an average velocity of about 1000 km/hr. The irregularities are more likely (about 50 per cent of the time) to fluctuate in intensity---growing and fading, on the average, in 10 minutes.

As indicated earlier there is no apparent correlation between record activity and magnetic activity unless it is on an instantaneous basis. It is possible, however, that the A_k indices obtained from Fort Belvoir are not sufficiently indicative of magnetic activity at the points of ionospheric reflection. If further work is attempted on this study, the magnetic activity should be looked into more closely. Other improvements of this study might include Doppler shift information, around the clock data, and more information on behavior in directions other than east.

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[13] This report has been limited to a radio frequency of 15 Mc., but small samplings have seemed to indicate that the behaviors mentioned are typical in the frequency range 15 Mc to 30 Mc.

[14] As opposed to movement toward the north. No attempt has been made to define east-west motion.

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